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Cok et al.

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(54) **IMPRINTED MULTI-LEVEL OPTICAL CIRCUIT STRUCTURE**

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H05K 3/12	(2006.01)
H01L 23/538	(2006.01)
H01L 21/768	(2006.01)
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G02B 6/13	(2006.01)
H01L 31/12	(2006.01)
H01L 31/18	(2006.01)
H05K 1/02	(2006.01)
G06F 3/044	(2006.01)
H05K 3/32	(2006.01)

(52) **U.S. Cl.**

CPC ***G02B 6/122*** (2013.01); ***G02B 6/13*** (2013.01); ***G02B 6/138*** (2013.01); ***G02B 6/4214*** (2013.01); ***G02B 6/4274*** (2013.01); ***H01L 21/76895*** (2013.01); ***H01L 23/5386*** (2013.01); ***H01L 31/12*** (2013.01); ***H01L 31/18*** (2013.01); ***H05K 3/1258*** (2013.01); *G02B 2006/121* (2013.01); *G02B 2006/12104* (2013.01); *G02B 2006/12126* (2013.01); *G02B 2006/12147* (2013.01); *G06F 3/044* (2013.01); *H01L 2924/0002* (2013.01); *H05K 1/0274* (2013.01); *H05K 3/32* (2013.01); *H05K 2201/0108* (2013.01); *H05K 2201/09036* (2013.01); *H05K 2201/10356* (2013.01); *H05K 2203/0108* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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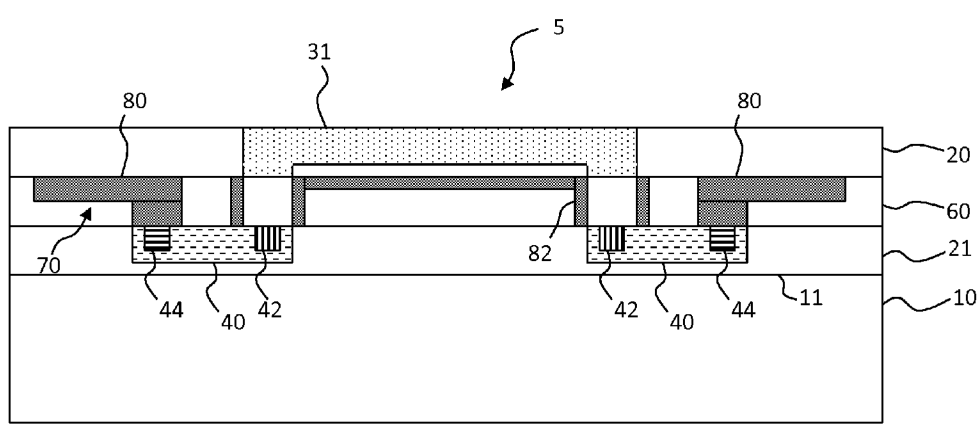
(74) *Attorney, Agent, or Firm* — Raymond L. Owens

(57) **ABSTRACT**

An imprinted optical micro-channel structure for transmitting light to an optical receiver or receiving light from an optical transmitter includes a substrate and a cured optical layer formed in relation to the substrate. The cured optical layer includes one or more optical micro-channels imprinted in the cured optical layer. Each optical micro-channel includes a cured light-transparent material forming a light-pipe that transmits light in the optical micro-channel. The optical transmitter is located in alignment with a light-pipe for transmitting light through the light-pipe or the optical receiver is located in alignment with a light-pipe for receiving light from the light-pipe.

7 Claims, 15 Drawing Sheets



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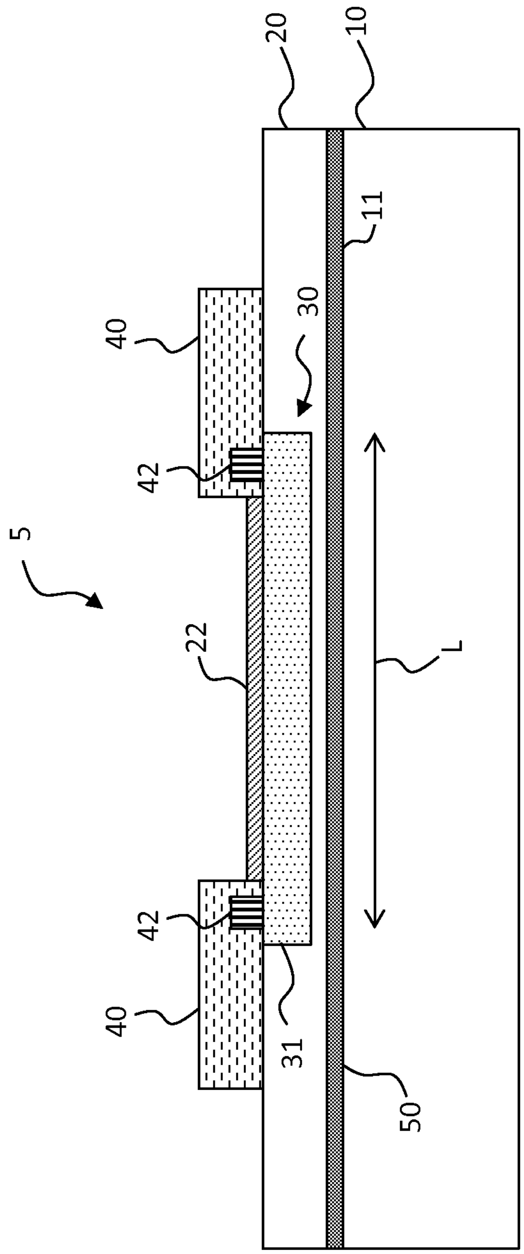


FIG. 1

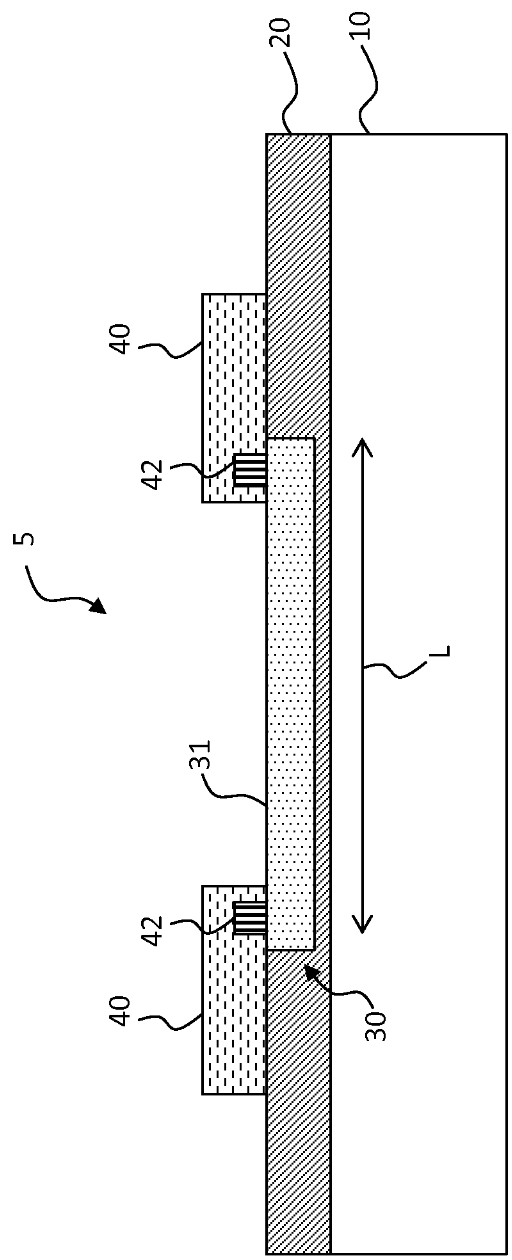


FIG. 2

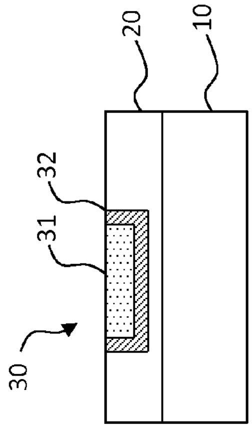


FIG. 3

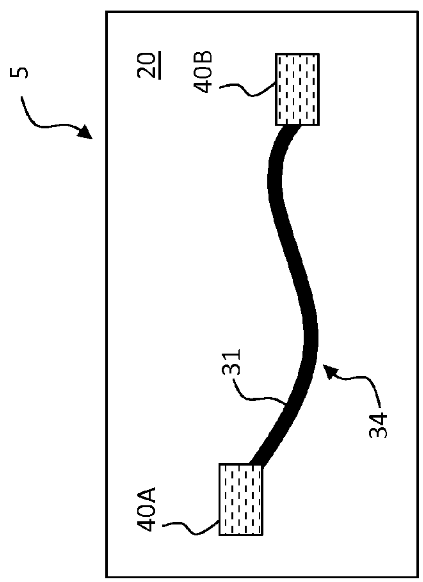


FIG. 4

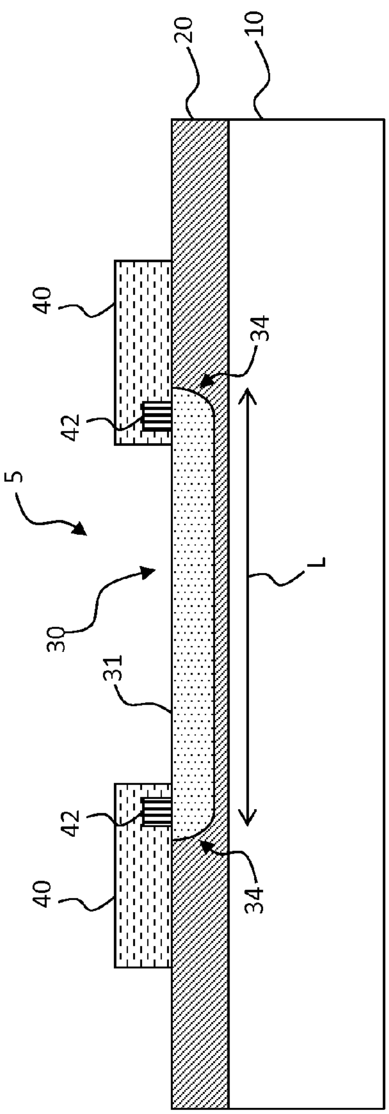


FIG. 5

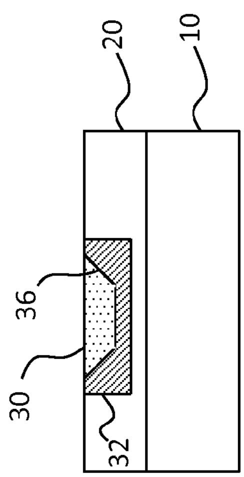


FIG. 6

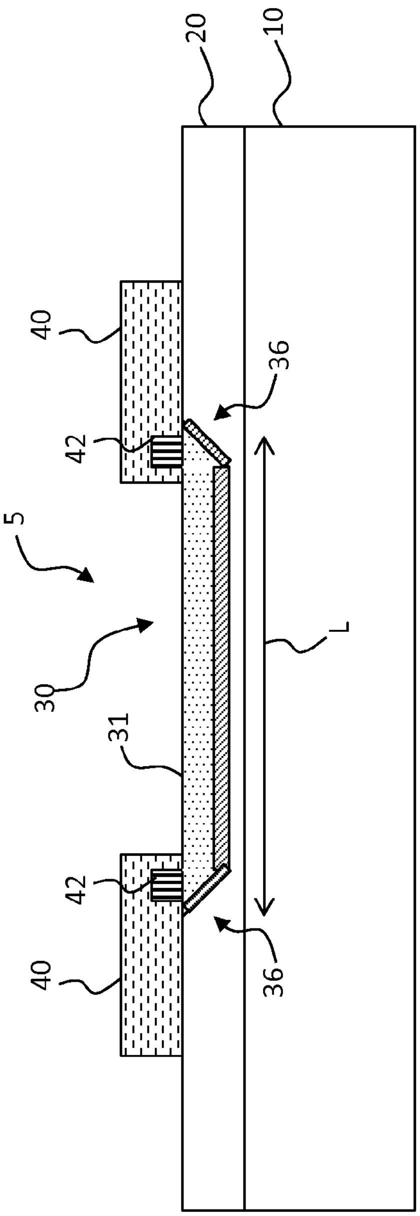


FIG. 7

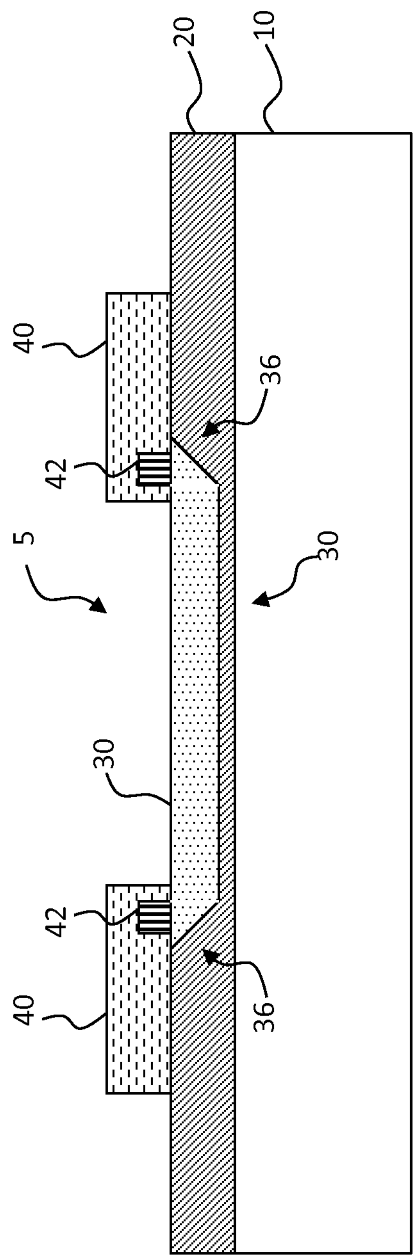


FIG. 8

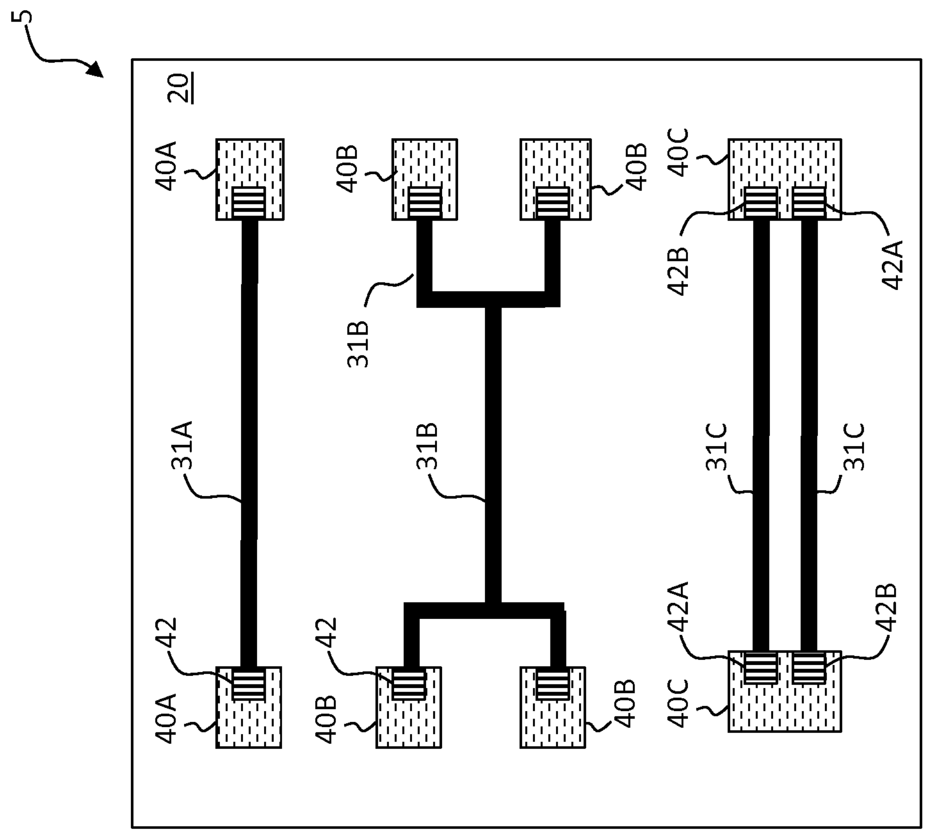

5
20
40A
40A
42
31A
40B
40B
40B
40B
42
31B
31B
40C
40C
42A
42B
42A
42B
31C
31C

FIG. 9

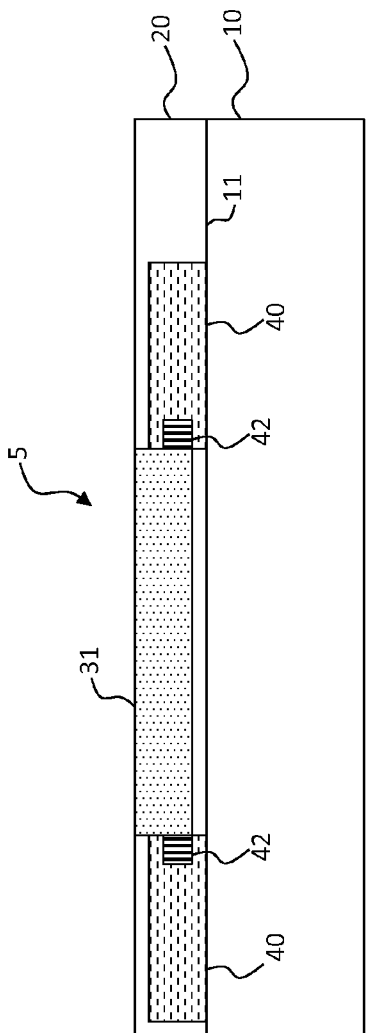


FIG. 10

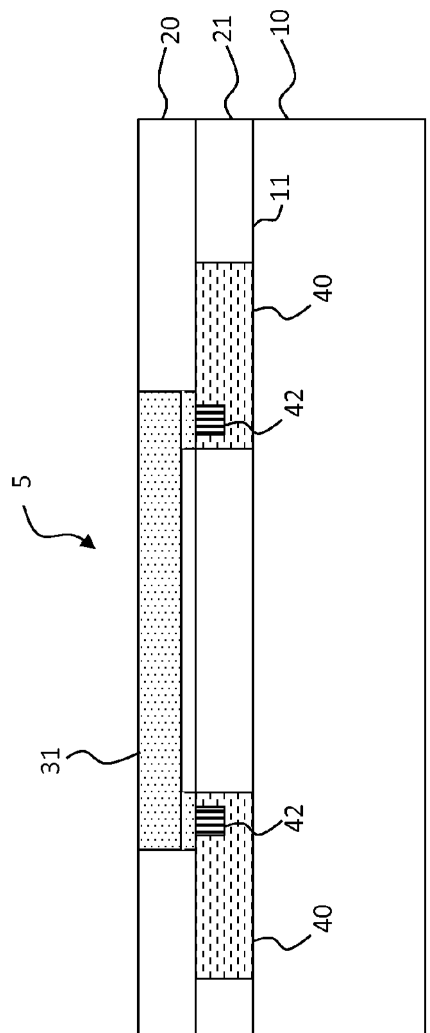


FIG. 11

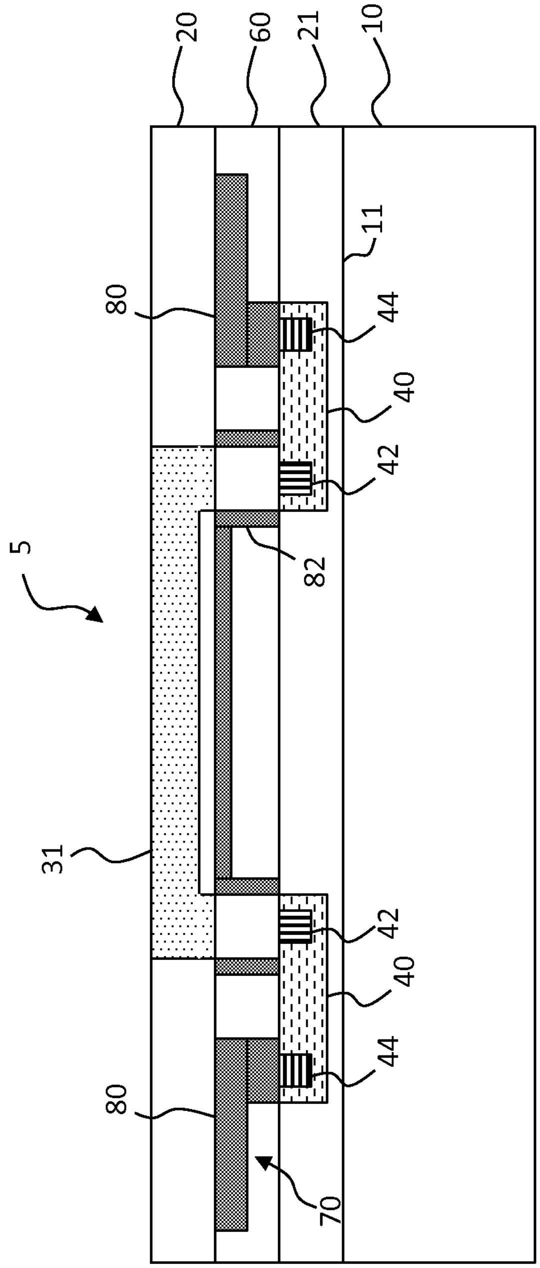


FIG. 12

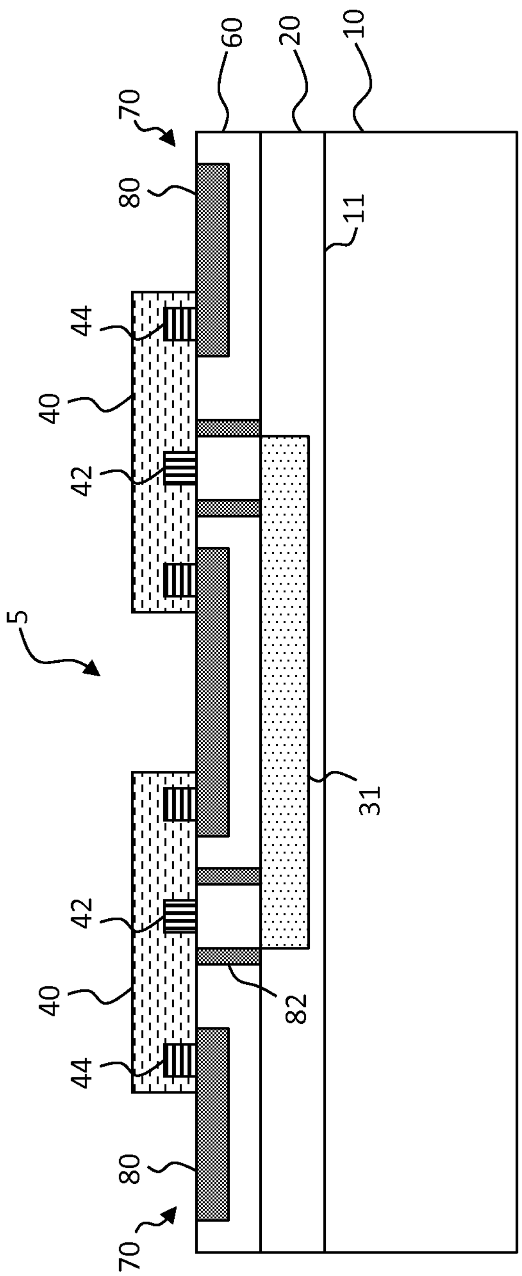


FIG. 13

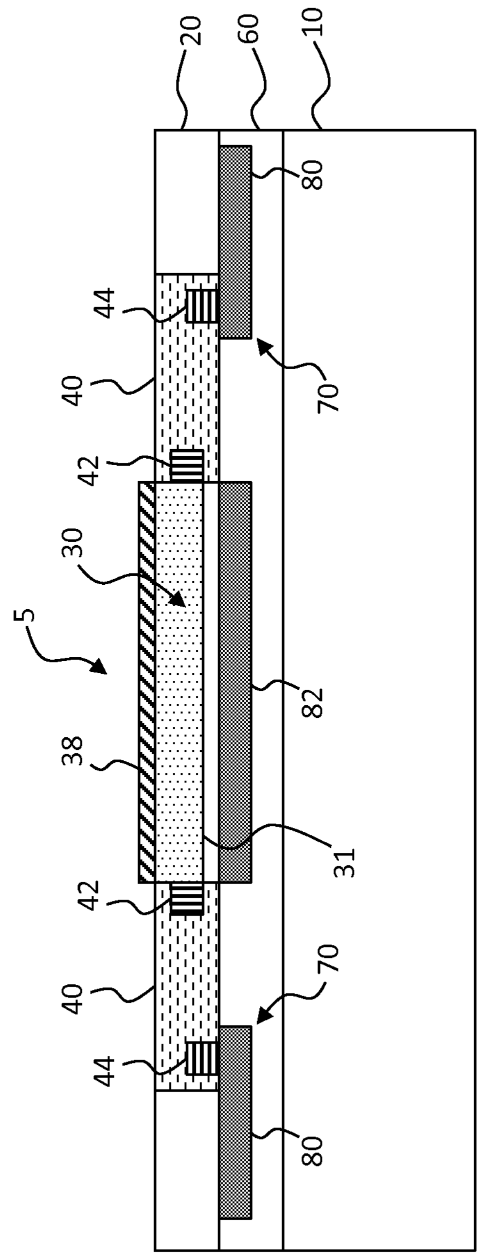


FIG. 14

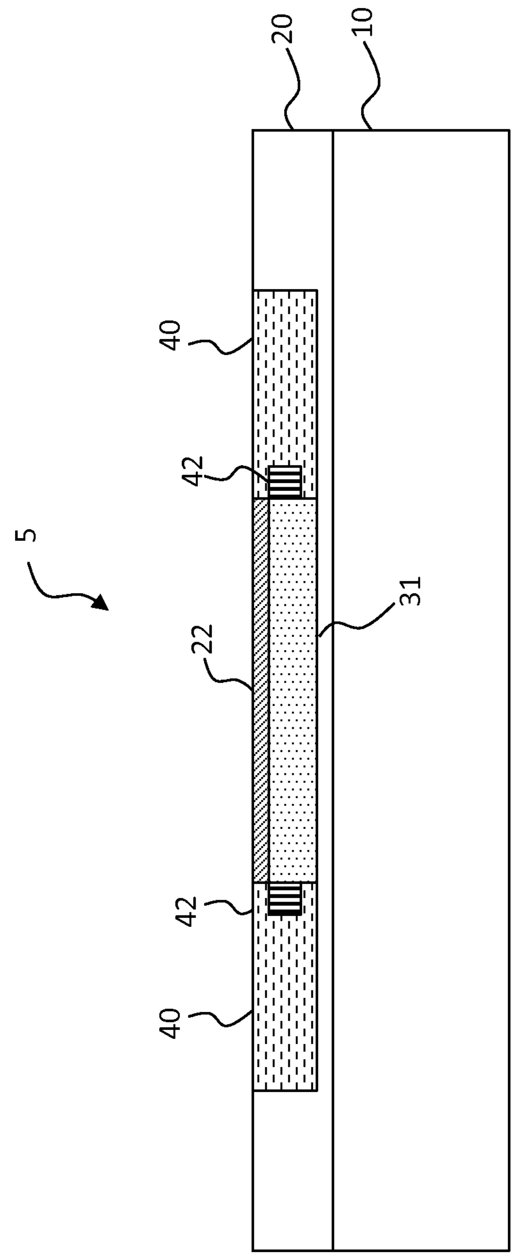


FIG. 15

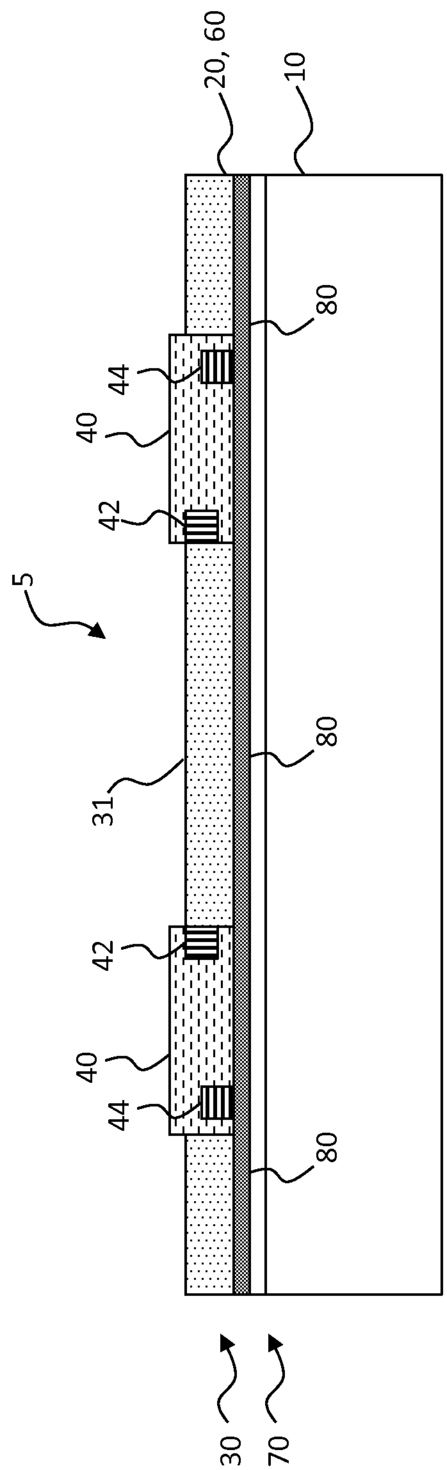


FIG. 16

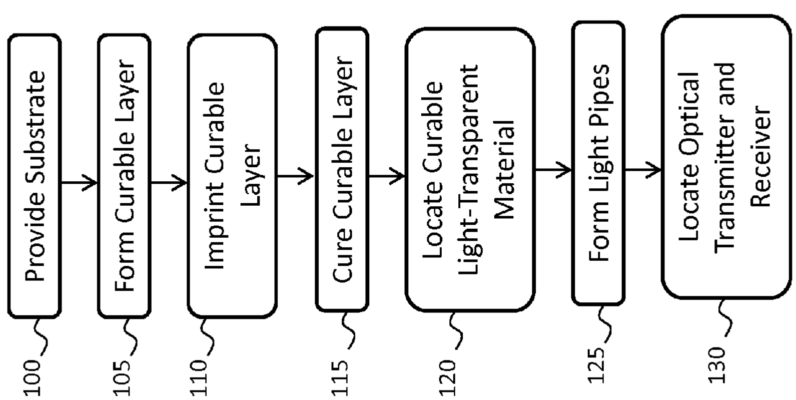


FIG. 17

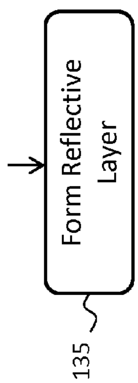


FIG. 18

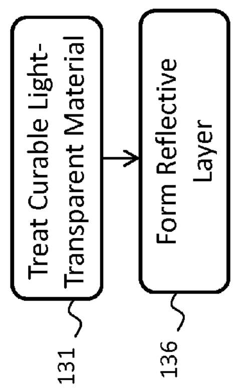


FIG. 19

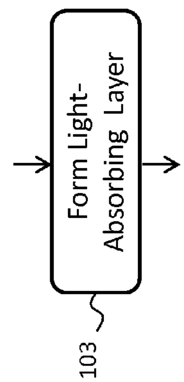


FIG. 20

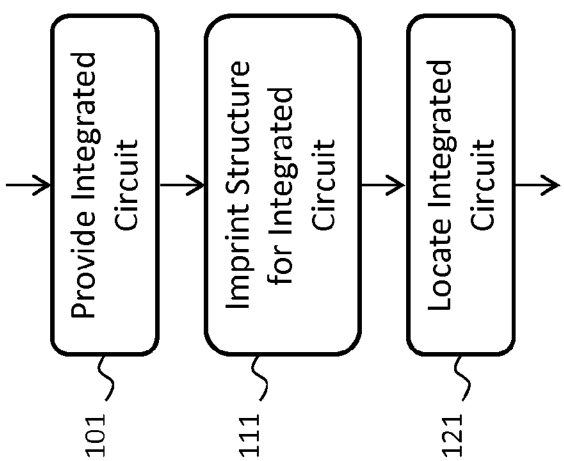

Provide Integrated Circuit
101
Imprint Structure for Integrated Circuit
111
Locate Integrated Circuit
121

FIG. 21

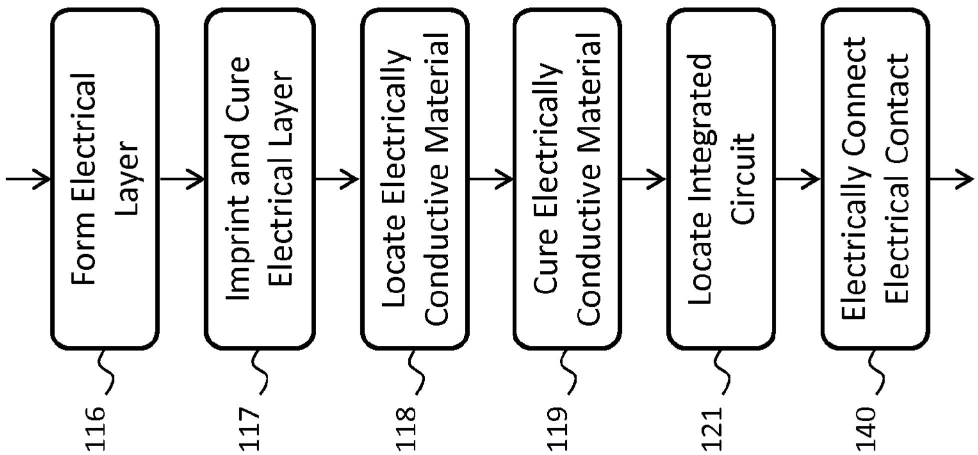

Form Electrical Layer
116
Imprint and Cure Electrical Layer
117
Locate Electrically Conductive Material
118
Cure Electrically Conductive Material
119
Locate Integrated Circuit
121
Electrically Connect Electrical Contact
140

FIG. 22

FIG. 23

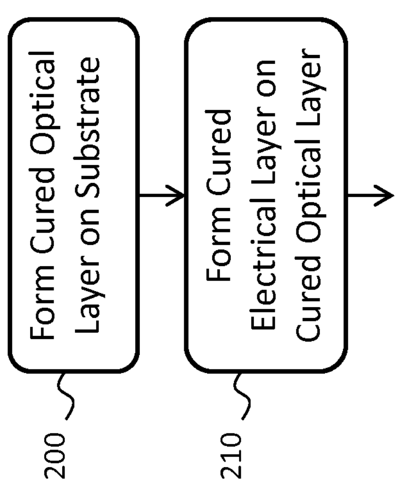
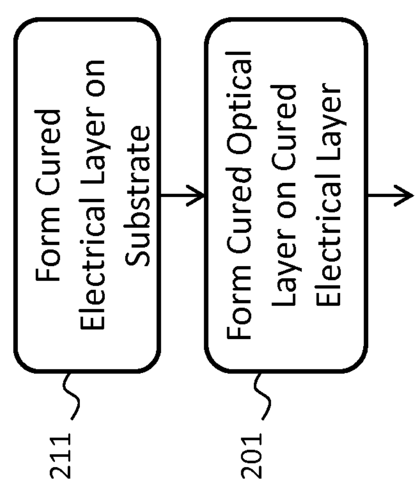

200
Form Cured Optical Layer on Substrate
210
Form Cured Electrical Layer on Cured Optical Layer

FIG. 24


211
Form Cured Electrical Layer on Substrate
201
Form Cured Optical Layer on Cured Electrical Layer

IMPRINTED MULTI-LEVEL OPTICAL CIRCUIT STRUCTURE

CROSS REFERENCE TO RELATED APPLICATIONS

Reference is made to commonly assigned U.S. patent application Ser. No. 14/012,195 (now U.S. Pat. No. 9,078, 360), filed Aug. 28, 2013, entitled "Imprinted Multi-level Micro-Structure" by Cok et al; U.S. patent application Ser. No. 14/012,269 (now U.S. Publication No. 2015/0060112), filed Aug. 28, 2013, entitled "Imprinted Bi-Layer Micro-Structure" by Cok; U.S. patent application Ser. No. 13/784, 869 (now U.S. Pat. No. 8,895,429), filed Mar. 5, 2013, entitled "Micro-Channel Structure with Variable Depths" by Cok; and U.S. patent application Ser. No. 14/097,812 (now U.S. Publication No. 2015/0160414) filed Dec. 5, 2013, entitled "Imprinted Multi-level Optical Circuit Structure Method" by Cok et al the disclosures of which are incorporated herein.

FIELD OF THE INVENTION

The present invention relates to optical circuits imprinted in a layer.

BACKGROUND OF THE INVENTION

Integrated circuits in a computing system typically communicate using electrical signals that pass through small wires embedded within a printed circuit board. Integrated circuits are also known that communicate with optical signals. Such optical signals have advantages in bandwidth and reduced electromagnetic interference. Some optical communication systems are proposed to use free-space, line-of-sight light propagation; others rely on integrated assemblies of light controlling elements.

Prior-art optical interconnection systems are often expensive, for example including elements such as embedded fiber optic cables, connectors, mirrors, holographic elements, and graded index materials or lenses. Such structures are difficult to make and assemble. U.S. Pat. No. 6,755,573 describes a full-mesh optical interconnect used in backplanes that includes power distribution. U.S. Pat. No. 6,320,863 illustrates another backplane structure with optical fiber communication. Micro-lenses associated with a corresponding optical transmission port are also known as disclosed in U.S. Pat. No. 8,437,085.

It is also known to make optical elements using imprinting methods for embossing a resin layer to form a plurality of micro-protrusions for an optical element, for example a brightness-enhancing sheet for a liquid-crystal display backlight module as describe in U.S. Patent Application Publication No. 2008/0079183.

SUMMARY OF THE INVENTION

There is a need for further improvements in methods and structures providing optical interconnections and electrical connectivity that enable simple and flexible manufacturing processes for a variety of applications. Such improved structures and processes according to the present invention are used to make a wide variety of optically interconnected computing circuits at a low cost and with high density.

In accordance with the present invention, an imprinted optical micro-channel structure for transmitting light to an optical receiver or receiving light from an optical transmitter comprises:

a substrate;

a cured optical layer formed in relation to the substrate, the cured optical layer including one or more optical micro-channels imprinted in the cured optical layer, each optical micro-channel including a cured light-transparent material forming a light-pipe that transmits light in the optical micro-channel; and

the optical transmitter located in alignment with a light-pipe for transmitting light through the light-pipe or the optical receiver located in alignment with a light-pipe for receiving light from the light-pipe.

The present invention provides improved structure and methods enable a wide variety of optically interconnected computing circuits at a low cost and with high density. Such improved optical interconnections enable computers or processors to communicate optically.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other features and advantages of the present invention will become more apparent when taken in conjunction with the following description and drawings wherein identical reference numerals have been used to designate identical features that are common to the figures, and wherein:

FIG. **1** is a cross-sectional view of an embodiment of the present invention;

FIG. **2** is a cross-sectional view of another embodiment of the present invention;

FIG. **3** is a cross-sectional view of a micro-channel taken orthogonally to the cross sections of FIGS. **1** and **2**;

FIG. **4** is a plan view of an embodiment of the present invention;

FIG. **5** is a cross-sectional view of yet another embodiment of the present invention;

FIG. **6** is a cross-sectional view of a micro-channel taken orthogonally to the cross sections of FIGS. **1**, **2**, and **5**;

FIGS. **7** and **8** are cross sectional views of other embodiments of the present invention;

FIG. **9** is a plan view of embodiments of the present invention;

FIGS. **10-16** are cross-sectional views of alternative embodiments of the present invention; and

FIGS. **17-24** are flow diagrams illustrating various methods of the present invention.

The Figures are not drawn to scale since the variation in size of various elements in the Figures is too great to permit depiction to scale.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed toward imprinted optical micro-channel structures for transmitting light to an optical receiver or receiving light from an optical transmitter. The light is typically modulated to form an optical signal. In one embodiment, the optical transmitter or optical receiver is formed in an electrically-powered semiconductor device or integrated circuit in a computing or communication system having a plurality of elements. In another embodiment, both the optical transmitter and optical receiver are formed in a single semiconductor device or integrated circuit that can both receive an optical signal from a single optical micro-channel and transmit an optical signal to the single optical micro-channel. Such an optical transmitter and optical receiver is referred to herein as an optical transceiver but, as intended herein, an optical transceiver includes either or both an optical transmitter or optical receiver. The light or optical signal can be visible, infrared, ultraviolet or any other form of electromagnetic radiation that is propagated in an optical micro-channel of the present invention.

Referring to FIG. **1**, in one embodiment of the present invention, an imprinted optical micro-channel structure **5** for transmitting light to an optical receiver or receiving light from an optical transmitter includes an optical transceiver **42** that is capable of either or both receiving and transmitting optical signals. In other embodiments (not shown in FIG. **1**), an optical receiver and an optical transmitter are separate elements and can operate at the same time, providing a full-duplex communication system, using for example a first optical micro-channel **30** for receiving a first optical signal and a separate second optical micro-channel **30** for simultaneously transmitting a different second optical signal. The optical receiver and the optical transmitter can be part of a single integrated circuit **40** or other semiconductor device or the optical receiver and the optical transmitter are part of separate integrated circuits **40** or other semiconductor devices. By providing optical transceivers **42** in integrated circuits **40**, more efficient computation and communication is enabled, since the integrated circuits **40** can include computational and control elements such as analog or digital circuits, thereby reducing the number and size of components and optical micro-channels **30** and simplifying the arrangements of the optical micro-channels **30**.

The imprinted optical micro-channel structure **5** includes a substrate **10**. A cured optical layer **20** is formed in relation to the substrate **10**, for example on a substrate surface **11** of the substrate **10** or a layer formed on the substrate surface **11** of the substrate **10**. The cured optical layer **20** includes one or more optical micro-channels **30** imprinted in the cured optical layer **20**. Each optical micro-channel **30** includes a cured light-transparent material forming a light-pipe **31** that transmits light in the optical micro-channel **30**. A light-transparent material is a material that permits light to travel emitted from an optical transmitter to an optical receiver through a light-pipe made of the light-transparent material. The optical transmitter (optical transceiver **42**) is located in alignment with the light-pipe **31** for transmitting light through the light-pipe **31** or the optical receiver (optical transceiver **42**) is located in alignment with the light-pipe **31** for receiving light from the light-pipe **31**.

The light-pipes **31** illustrated in the Figures are formed in the optical micro-channels **30** and are therefore not readily distinguished in the illustrations. For clarity, the optical micro-channels **30** in which the light-pipes **31** are formed are labeled with corresponding numbered arrows pointing to the optical micro-channels **30**. The light-pipes **31** formed in the corresponding optical micro-channels **30** are labeled with numbered lead lines touching the light-pipes **31**.

In operation, the integrated circuits **40** control the optical transceivers **42** to send and receive optical signals to and from each other through the light-pipes **31**. In the case in which the optical transceivers **42** are formed in the integrated circuits **40**, the integrated circuits **40** are thereby communicating to perform, for example, computation or communication tasks.

In one embodiment of the present invention, the cured optical layer **20** has an optical index and the cured light-transparent material in the light-pipe **31** has an optical index greater than the optical index of the cured optical layer **20**. Thus, light emitted along a length direction L of the light-pipe **31** can experience total internal reflection and thereby propagate effectively along the light-pipe **31** from one optical transceiver **42** to another optical transceiver **42**.

In another embodiment of the present invention, the imprinted optical micro-channel structure **5** includes a reflective layer **22** in contact with the cured optical layer **20**. The reflective layer **22** reflects light that might escape from the light-pipe **31** back into the light-pipe **31** or towards the optical transceivers **42**, thereby increasing the optical signal and reducing cross-talk between adjacent light-pipes **31**. In an embodiment, the reflective layer **22** is located on an opposite side of the light-pipe **31** from the substrate **10** (as shown in FIG. **1**). In another embodiment, the reflective layer **22** is located between the light-pipe **31** and the substrate **10** (not shown).

In a further embodiment of the present invention, the imprinted optical micro-channel structure **5** includes a light-absorbing layer **50** located between the cured optical layer **20** and the substrate **10** (as shown) or located with the cured optical layer **20** between the light-absorbing layer **50** and the substrate **10** (not shown). The light-absorbing layer **50** can absorb light that escapes from the light-pipe **31** and prevent the escaped light from entering other light-pipes **31** to prevent cross-talk or otherwise improve the signal-to-noise ratio of the optical signals propagated within the light-pipes **31**. In an embodiment, the cured optical layer **20** is formed on the light-absorbing layer **50**.

Referring to FIG. **2**, light emitted from the optical transceiver **42** in the integrated circuit **40** mounted in relation to the substrate **10** in an imprinted optical micro-channel structure **5** can be controlled to stay within a light-pipe **31** by forming the cured optical layer **20** from a light-reflective material so that the cured optical layer **20** is reflective and the optical micro-channels **30** are defined by reflective walls. Alternatively, referring to FIG. **3** in a cross-sectional view of the light-pipe **31** formed in the cured optical layer **20** on the substrate **10** taken orthogonally to the length direction L of the light-pipe **31** (FIG. **2**), the light-pipe **31** has a reflective micro-channel wall **32** that reflects light propagating through the light-pipe **31**. By providing light-reflective material around a light-pipe **31** or providing reflective micro-channel walls **32**, light propagating through the light-pipes **31** is prevented from escaping from the light-pipes **31**, thereby increasing the optical signal and reducing cross-talk between adjacent light-pipes **31**.

Referring to FIGS. **4**-**7**, in various embodiments the imprinted optical micro-channel structure **5** includes the optical micro-channels **30** imprinted in the cured optical layer **20** on the substrate **10** that are curvilinear or include reflective portions for directing light along the length of the optical micro-channels **30**. The light is emitted or received by the optical transceivers **42** in the integrated circuits **40**. By providing curvilinear optical micro-channels **30**, a greater variety of arrangements of the optical transceivers **42** and the integrated circuits **40** over the substrate **10** is enabled, thereby enabling a greater variety of imprinted optical micro-channel structure **5** designs. By providing reflective portions in the optical micro-channels **30**, light propagating through the light-pipes **31** is prevented from escaping from the light-pipes **31**, thereby increasing the optical signal and reducing cross-talk between adjacent light-pipes **31**.

Referring specifically to FIG. **4** in plan view, the light-pipe **31** has curved micro-channel portions **34** and extends from integrated circuit **40**A to integrated circuit **40**B. As shown in FIG. **5**, the light-pipe **31** in cross section includes curved micro-channel portions **34** that reflect light emitted from the optical transceiver **42** along the length direction L of the light-pipe **31** or that reflects light traveling along the length direction L of the light-pipe **31** into the optical transceiver **42**. Referring to FIG. **6**, in a cross-sectional view of a light-pipe **31** formed in the cured optical layer **20** on substrate **10** taken orthogonally to the length direction L of the light-pipe **31**

(FIG. 5) and to FIG. 7 in a cross sectional view taken along the length direction L of light-pipe **31**, the light-pipe **31** has reflective angled micro-channel portions **36**. In FIGS. **6** and **7**, the reflective angled micro-channel portion **36** is a reflective micro-channel wall **32**. In FIG. **8**, the cured optical layer **20** is reflective (as in FIG. **2**) forming the reflective angled micro-channel portion **36**. The reflective angled micro-channel portions **36** of FIG. **6** are orthogonal to the reflective angled micro-channel portions **36** of FIGS. **7** and **8** and both can be incorporated into a common light-pipe **31**. In any case, light emitted from the optical transceiver **42** in the integrated circuit **40** is reflected along the length direction L of the light-pipe **31** to another optical transceiver **42** in another integrated circuit **40**.

Referring to FIG. **9**, in various embodiments of the imprinted optical micro-channel structure **5**, one or more integrated circuits **40**A, **40**B, **40**C located on or in the cured optical layer **20** has one or more optical transceivers **42**. Each optical transceiver **42** is located in alignment with at least one associated light-pipe **31**A, **31**B, **31**C. The optical transceiver **42** transmits light into the associated light-pipe **31** or receives light from the associated light-pipe **31**.

In FIG. **9**, the integrated circuits **40**A each have one optical transceiver **42** that emits and receives light through the light-pipe **31**A. Only two optical transceivers **42** in integrated circuits **40**A are aligned with light-pipe **31**A. In contrast, the light-pipe **31**B is aligned with the optical transceiver **42** in each of the four integrated circuits **40**B. In this arrangement, the light-pipe **31**B serves as a common optical communication link forming an optical buss for the integrated circuits **40**B. Alternatively, the integrated circuits **40**C each have one optical transmitter **42**A and one optical receiver **42**B. Each light-pipe **31**C transmits light emitted by the optical transmitter **42**A to the optical receiver **42**B, forming a full-duplex communication system capable of simultaneously transmitting optical signals and receiving optical signals.

The three arrangements of FIG. **9** can be combined in an optical communication structure in the cured optical layer **20** so that one or more integrated circuits **40** have one or more optical transceivers **42**, one or more optical transmitters **42**A, or one or more optical receivers **42**B. Similarly, the light-pipes **30**A, **30**B, **30**C can be used in a common optical communication structure so that some optical transceivers **42** are connected in a bi-directional point-to-point arrangement (as shown with light-pipe **31**A), a shared arrangement (as shown with light-pipe **31**B), or a full-duplex arrangement that exclusively transmits optical signals from one optical transmitter **42**A to an optical receiver **42**B (as shown with light-pipe **31**C). Alternatively, the optical transmitter **42**A can broadcast optical signals to multiple optical receivers **42**B or to multiple optical transceivers **42** through a light-pipe **31** (not shown).

In one embodiment, the optical transceivers **42** are located in the integrated circuits **40** on the cured optical layer **20**, as shown in FIG. **1**. In another embodiment, the optical transceivers **42** are located in the integrated circuits **40** and at least partly in the cured optical layer **20**. Referring to FIG. **10**, the integrated circuits **40** having the optical transceivers **42** are located in the cured optical layer **20** on the substrate surface **11** of the substrate **10**. The optical transceivers **42** are optically connected by light-pipe **31** to form an imprinted optical micro-channel structure **5** of the present invention. Alternatively, referring to FIG. **11**, the integrated circuits **40** having the optical transceivers **42** are located in the layer **21** formed between the cured optical layer **20** and the substrate surface **11** of the substrate **10**. In an embodiment, the layer **21** is a cured layer similar to the cured optical layer **20** formed in a separate step. The optical transceivers **42** are optically connected by the light-pipe **31** to form an imprinted optical micro-channel structure **5** of the present invention. In this embodiment, the light-pipe **31** can be a multi-layer light-pipe **31** to facilitate the propagation of light through the light-pipe **31**.

Referring to FIGS. **12** and **13**, in a further embodiment of the present invention, the imprinted optical micro-channel structure **5** includes a cured electrical layer **60** in contact with the cured optical layer **20** and formed on the layer **21** on the substrate surface **11** of the substrate **10** (FIG. **12**) or formed on the cured optical layer **20**. The integrated circuits **40** having the optical transceivers **42** are located adjacent to the cured electrical layer **60** in the layer **21** (FIG. **12**) or on the cured electrical layer **60** opposite the cured optical layer **20** (FIG. **13**). The cured electrical layer **60** includes electrical micro-channels **70** imprinted in the cured electrical layer **60**. The electrical micro-channels **70** include a cured electrically conductive material forming micro-wires **80** in the electrical micro-channels **70**. The integrated circuit **40** further includes one or more electrical contacts **44**. Each electrical contact **44** is electrically connected to at least one micro-wire **80**.

Micro-wires **80** illustrated in the Figures are formed in electrical micro-channels **70** and are therefore not readily distinguished in the illustrations. For clarity, the electrical micro-channels **70** in which the micro-wires **80** are formed are labeled with corresponding numbered arrows pointing to the electrical micro-channels **70**. The micro-wires **80** formed in the corresponding electrical micro-channels **70** are labeled with numbered lead lines touching the micro-wires **80**.

By providing the cured electrical layer **60** with electrical micro-channels **70**, and micro-wires **80**, electrical power and signals are provided to the integrated circuits **40** and optical transceivers **42** in a solid-state structure.

As shown in the embodiment of FIG. **12**, the cured electrical layer **60** is located between the cured optical layer **20** and the substrate **10**. Alternatively, as shown in FIG. **13**, the cured optical layer **20** is located between the cured electrical layer **60** and the substrate **10**.

In the embodiment of FIG. **12**, the light-pipe **31** is a multi-layer light-pipe **31** optically connecting the optical transceivers **42**. In a further embodiment, at least one micro-wire **80** is a reflective micro-wire **82** and is located to reflect light transmitted by the optical transceiver **42**, for example through the cured electrical layer **60** from the optical transceiver **42** to the light-pipe **31**. Alternatively or in addition, the reflective micro-wire **82** is located along the length direction L (FIG. **1**) of an optical micro-channel **30**, thereby facilitating the propagation of light through the light-pipe **31** to increase the optical signal and reduce cross-talk between the light-pipes **31**. Both of these structures are shown in both FIGS. **12** and **13**. FIGS. **12** and **13** show similar structures but are alternative embodiments that are reversed with respect to the substrate **10**.

Referring to FIG. **14**, in yet another embodiment, the optical micro-channel **30** includes an optical structure **38** that processes light propagating along light-pipe **31**, thereby modifying optical signals propagating in the light-pipe **31**, for example to improve the optical signal by filtering or redirecting the optical signal. The optical structure **38** is formed either in the light-pipe **31** or adjacent to the light-pipe **31**, for example in optical contact with the cured optical layer **20** or with the cured electrical layer **60**. In this embodiment, the cured electrical layer **60** is located between the cured optical layer **20** and the substrate **10**. The cured electrical layer **60** includes the micro-wires **80** formed in the electrical micro-channels **70** electrically connected to electrical contacts **44** of integrated circuits **40** and reflective micro-wire **82**. Optical transceivers **42** in integrated circuits **40** emit light into light-pipe **31** or receive light from light-pipe **31**.

Referring to FIG. **15**, in another embodiment, the optical micro-channel **30** is partially filled with light-transparent material and partially filled with the reflective layer **22**. The reflective layer **22** reflects light along the light-pipe **31** to improve the optical signal and prevent cross-talk between light-pipes **31**. Optical transceivers **42** in integrated circuits **40** emit light into the light-pipe **31** or receive light from the light-pipe **31**. The integrated circuits **40** are located in the cured optical layer **20**. In FIG. **15**, the reflective layer **22** is located on the light-pipe **31** opposite the substrate **10**. In an alternative arrangement (not shown), the reflective layer is located between the light-pipe **31** and the substrate **10**.

Referring to FIG. **16**, in another embodiment, the cured electrical layer **60** and the cured optical layer **20** are a common layer. The micro-wires **80** are located between the light-pipes **31** and the substrate **10**. Alternatively, the light-pipes **31** are located between the micro-wires **80** and the substrate **10** (not shown). In these embodiments, the optical and electrical micro-channels **30**, **70** are common micro-channels (although they can be multi-layer micro-channels) with two sub-layers, one sub-layer including the micro-wires **80** and the other sub-layer including the light-pipes **31**. The micro-wires **80** can reflect light propagating through the light-pipes **31** from the optical transceivers **42** of the integrated circuits **40** and are also electrically connected to the electrical contacts **44** of the integrated circuits **40**. The micro-wires **80** thus provide both electrical power and signals and reflect stray light as a reflective micro-wire **82** (not indicated). The sub-layer furthest from the substrate **10** is a spatial superset of the sub-layer closer to the substrate **10**. In this embodiment, every micro-channel is both an optical and electrical micro-channel **30**, **70**. However, not all of the electrical micro-wires **80** need be electrically connected to an electrical contact **40**. Nor does every light-pipe need to be connected to an optical transceiver **42**. The structure of FIG. **16** usefully reduces the number of imprinting steps needed to make the optical and electrical micro-channels **30**, **70**.

In one embodiment of the present invention, the optical transmitter or receiver (optical transceiver **42**) is an edge optical transmitter or receiver (as shown in FIGS. **10** and **14**-**16**). In another embodiment, the optical transmitter or receiver (optical transceiver **42**) is a surface optical transmitter or receiver (as shown in FIGS. **1** and **2**). The optical transmitter can be a light-emitting diode or laser diode. The optical receiver can be a light-sensitive semiconductor junction, for example as found in silicon diodes. Such edge or surface optical transmitters are known in the art, as are light-sensitive semiconductor elements, for example diodes or transistors found in integrated circuits.

Referring to FIG. **17**, a method of making an imprinted optical micro-channel structure **5** for transmitting light to an optical receiver or receiving light from an optical transmitter according to an embodiment of the present invention includes providing a substrate **10** in Step **100** and forming a curable optical layer **20** over the substrate **10** in Step **105**. One or more optical micro-channels **30** are imprinted in the curable optical layer **20** with a first stamp in Step **110**. The curable optical layer **20** is cured in Step **115** to form a cured optical layer **20** having the optical micro-channels **30** imprinted in the cured optical layer **20**. The provision of substrates **10** is known in the art as are ways to coat curable materials on the substrate **10** and imprinting the curable materials, for example using imprinting stamps.

A curable light-transparent material is located in Step **120** in the optical micro-channels **30** and cured to form light-pipes **31** of cured light-transparent material in the optical micro-channels **30** (Step **125**). Curable light-transparent materials are known having a variety of optical indices (for example resins or epoxies of various types with optical indices of between 1.3 and 1.8 having fluorine or sulfur compounds) and can be coated using conventional methods, e.g. curtain, hopper, blade, or spin coating. An optical transmitter or receiver, or an optical transceiver **42** including either or both an optical transmitter or receiver, is located on the cured optical layer **20** in Step **130** in alignment with the light-pipe **31** for transmitting light through the light-pipe **31** or locating the optical receiver in alignment with a light-pipe **31** for receiving light from the light-pipe **31**. In an embodiment, the optical transceiver **42** is part of an integrated circuit **40** and is adhered to the imprinted optical micro-channel structure by the materials making up the cured optical layer **20**. An optical transmitter or receiver, or an optical transceiver **42**, is made using known photolithographic methods in integrated circuit manufacturing.

In a further embodiment as illustrated in FIG. **18**, the reflective layer **22** is formed in contact with the cured optical layer **20** in Step **135** after the curable light-transparent material is cured. The reflective layer **22** can extend generally over the integrated circuit **40** and portions of the cured optical layer **20** (not shown). In an embodiment the integrated circuit **40** and portions of the cured optical layer **20** are masked to prevent deposition of light-reflective material in unwanted areas. The deposition of light-reflective materials (for example metals) is known in the art, for example by sputtering, evaporation, or atomic layer deposition, as are photolithographic patterning methods. In another embodiment, the reflective layer **22** is formed on the walls of the optical micro-channel **30**, for example by sputtering, evaporation, or atomic layer deposition processes. To prevent unwanted deposition, portions of the cured optical layer **20** can be masked using conventional photolithographic techniques. In an alternative embodiment, the reflective layer **22** is formed between the cured optical micro-channel **30** and the substrate **10** by conventional deposition methods.

In an alternative or additional embodiment illustrated in FIG. **20**, the light-absorbing layer **50** is formed in Step **103** between the cured optical layer **20** and the substrate **10**, for example using coating processes and materials known in the art, for example spin or hopper coating with resins impregnated with light-absorbing particles, such as carbon black.

A wide variety of arrangements of reflective layers **22** or light-absorbing layers **50** are contemplated as part of the present invention. The reflective layers **22** and light-absorbing layers **50** are located to control the propagation of light from one optical transceiver **42** to another optical transceiver **42**. The reflective layer **22** directs light along the light-pipes **31** to increase the optical signal and prevent light from escaping from the light-pipes. The light-absorbing layer **50** absorbs stray light and reduces noise in the optical system.

In another embodiment, reflective portions of the optical micro-channels **30** are formed by using a shaped stamp. The shapes impressed in the optical micro-channels **30** can direct light along the length of the optical micro-channels **30**. For example, angled or curved micro-channels portions **34**, **36** improve light reflection around a corner or curve and are impressed with an imprinting stamp. Methods for forming impressing stamps are known in the art.

In a further embodiment of the present invention and as illustrated in FIG. **21**, one or more integrated circuits **40** having one or more optical transceivers **42** is located with the optical transceivers **42** in alignment with a corresponding one or more light-pipes **31**. An integrated circuit **40** is provided in

Step **101** and located in Step **121**. The integrated circuit **40**, in various embodiments, is located on the substrate surface **11** of the substrate **10**, between the cured optical layer **20** and the substrate **10**, in the cured optical layer **20**, or on the cured optical layer **20** opposite the substrate **10**. In embodiments, the integrated circuit **40** is located by stamping or by pick-and-place methods known in the manufacturing arts. In one embodiment, the curable optical layer **20** or curable electrical layer **60** in Step **111** is imprinted to form an impression in which the integrated circuit **40** is located. Such an impression can help align the optical transceiver **42** with a light-pipe **31** and can be performed in a common step with imprinting the optical micro-channels **30** or electrical micro-channels **70**.

In another embodiment illustrated in FIG. **19**, the curable light-transparent material in the optical micro-channel **30** is treated in Step **131** to reduce the size of the light-transparent material for example, by curing and shrinking with heat or radiation, or removing solvents from the curable light-transparent materials by drying. The light-transparent material then only fills a portion of the optical micro-channel **30**. In Step **136**, a reflective material is located in the optical micro-channel **30** with the cured light-transparent material to form a reflector for controlling light propagating in the optical micro-channel **30**. Alternatively, the light-transparent material located in the optical micro-channel **30** does not fill the optical micro-channel **30** when coated over the cured optical layer **20** and the reflective material is located in the optical micro-channel **30** before the light-transparent material is cured. In another embodiment, the reflective material is deposited in the optical micro-channel **30** before the light-transparent material. In various embodiments, reflective material is deposited with or without masking by sputtering or evaporation, or liquid materials with reflective components (such as is the case with conductive inks) are coated and cured.

In a further embodiment of the present invention, referring to FIG. **22**, the curable electrical layer **60** is formed in contact with the cured optical layer **20** in Step **116**. The electrical micro-channels **70** are imprinted in the curable electrical layer **60** and cured in Step **117**. In an embodiment, the provision and curing of the curable electrical layer **60** and the imprinting of the electrical micro-channels is done using the same materials and processes as are used for the curable optical layer **20**.

A curable electrically conductive material is located in the electrical micro-channels for example by coating and wiping, in Step **118** and cured in Step **119** to form a micro-wire **80** each of the electrical micro-channels **70**. Coating and wiping methods for conductive inks are known, as are inkjet deposition methods for example as disclosed in U.S. patent application Ser. No. 14/012,195, filed Aug. 28, 2013, entitled “Imprinted Multi-level Micro-Structure” by Cok et al; U.S. patent application Ser. No. 14/012,269, filed Aug. 28, 2013, entitled “Imprinted Bi-Layer Micro-Structure” by Cok; and U.S. patent application Ser. No. 13/784,869, filed Mar. 5, 2013, entitled “Micro-Channel Structure with Variable Depths” by Cok; the disclosures of which are incorporated herein.

Integrated circuits **40** with electrical contacts **44** are located in alignment with the micro-wires **80** in Step **121** and electrically connected in Step **140**. In one embodiment, the electrical contacts **44** are coated with electrically conductive connecting materials, such as solder or anisotropic conductive film and treated, for example by heat, pressure, or radiation to form the electrical connections between at least one micro-wire **80** and one electrical contact **44**. Such electrical-connection materials and electrical-connection processes are known in the art.

In various embodiments illustrated in FIGS. **23** and **24**, the cured electrical layer **60** is located between the cured optical layer **20** and the substrate **10** or the cured optical layer **20** is located between the cured electrical layer **60** and the substrate **10**. The various layers are located in various relative positions by forming, impressing, curing, and filling the micro-channels in each layer in different orders. As illustrated in FIG. **23**, the cured optical layer **20** is formed in Step **200** on the substrate **10** and the cured electrical layer **60** is subsequently formed on the cured optical layer **20** in Step **210**. Alternatively, as illustrated in FIG. **24**, the cured electrical layer **60** is formed in Step **211** on the substrate **10** and the cured optical layer **20** is subsequently formed on the cured electrical layer **60** in Step **201**. Similarly, the location of the integrated circuits **40** in the layers is controlled by the order in which the integrated circuits are placed in the layers relative to the formation of the layers and corresponding micro-channels.

In other embodiments, at least one micro-wire is located to reflect light transmitted by an optical transceiver. The at least one reflective micro-wire **82** is located along the length of an optical micro-channel **30** or is located to reflect light from the optical transceiver **42** to the optical micro-channel **30**. The location of reflective elements is controlled, for example by shaping the imprinting stamp to form corresponding structures in either the cured optical layer **20** or the cured electrical layer **60** or by depositing material over one or more of the cured electrical or cured optical layers **60**, **20**, either with a pattern-wise deposition or a blanket deposition with or without subsequent patterning for example with masking or etching.

According to various embodiments of the present invention, the substrate **10** is any material having a substrate surface **11** on which the cured optical layer **20** is formed. The substrate **10** is a rigid or a flexible substrate made of, for example, a glass, metal, plastic, or polymer material, with or without additional layers formed thereon, and can have opposing substantially parallel and extensive surfaces. The substrates **10** can include a dielectric material and can have a wide variety of thicknesses, for example 10 microns, 50 microns, 100 microns, 1 mm, or more. In various embodiments, the substrate **10** is transparent, for example transmitting 50%, 80%, 90%, 95% or more of light emitted by the optical transmitter. Materials and manufacturing processes for making suitable substrates **10** and substrate surfaces **11** on which layers are coated are known in the art. The substrate **10** can be an element of other devices, for example the cover or substrate of a display or a substrate, cover, or dielectric layer of a touch screen.

The cured optical layer **20** is a layer of curable material that has been cured and, for example, formed of a curable material coated or otherwise deposited on a surface, for example the substrate surface **11** of the substrate **10**, to form a curable layer. The substrate-coated curable material is considered herein to be curable layer before it is cured and a cured layer after it is cured.

In various embodiments, curable layers are deposited as a single layer in a single step using coating methods known in the art, e.g. curtain coating, hopper coating, or blade coating. In an alternative embodiment, curable layers are deposited as multiple sub-layers using multi-level deposition methods known in the art, e.g. multi-level slot coating, repeated curtain coatings, or multi-level extrusion coating. In yet another embodiment, curable layers include multiple sub-layers formed in different, separate steps, for example with a multi-level extrusion, curtain coating, or slot coating as is known in the coating arts.

Cured layers (e.g. the cured optical layer **20**) useful in the present invention can include a cured polymer material, such as resin, with cross-linking agents that are sensitive to heat or radiation, for example infra-red, visible light, or ultra-violet radiation. SU-8 is such a useful material. The polymer material can be a curable material applied in a liquid form that hardens when the cross-linking agents are activated, for example with exposure to radiation or heat.

When a molding device, such as an imprinting stamp having an inverse micro-channel structure is applied to liquid curable material in a curable layer coated on the substrate **10** and the cross-linking agents in the curable material are activated, the liquid curable material in the curable layer is hardened into the cured optical layer **20** having optical micro-channels **30** or the cured electrical layer **60** having electrical micro-channels **70** with the inverse structure of the stamp. The liquid curable materials can include a surfactant to assist in controlling coating. Materials, tools, and methods are known for imprinting coated liquid curable materials to form cured layers having optical or electrical micro-channels **30**, **70**.

In some embodiments, an optical or electrical micro-channel **30**, **70** is a groove, trench, or channel formed in the cured optical layer **20** or cured electrical layer **60** and having a cross-sectional width less than 20 microns, for example 10 microns, 5 microns, 4 microns, 3 microns, 2 microns, 1 micron, or 0.5 microns, or less. In an embodiment, a micro-channel depth is comparable to a micro-channel width. Optical or electrical micro-channels **30**, **70** can have a rectangular cross section, as shown in the Figures. Other cross-sectional shapes, for example trapezoids, are known and are included in the present invention. The width or depth of a layer is measured in cross section.

In an embodiment, optical or electrical micro-channels **30**, **70** are imprinted and cured in curable layers in a single step and micro-wires **80** are formed by depositing a curable conductive ink in electrical micro-channels **70** and curing the curable conductive ink to form an electrically conductive micro-wire **80**. Micro-wires **80** are formed in electrical micro-channels **70** by locating, e.g. by coating, liquid conductive materials, for example curable conductive inks, into the electrical micro-channels **70** and curing the liquid conductive materials to form micro-wires **80**. The micro-wires **80** can be less than 20 microns wide, less than 10 microns wide, less than 5 microns wide, less than 2 microns wide, or less than one micron wide. According to an embodiment of the present invention, the substrate **10**, the cured optical layer **20**, and the cured electrical layer **60** are substantially transparent (for example more than 50%, 70%, 80%, 90%, or 95% transparent to visible light) and the micro-wires **80** are imperceptible to the unaided human visual system. Furthermore, in an embodiment the micro-wires **80** are substantially uniformly distributed over the substrate **10** so that the light absorbed or reflected by the micro-wires **80** is uniform over the substrate **10** and the imprinted multi-channel structure **5** of the present invention has a uniform appearance.

Curable conductive inks useful in the present invention are known and can include conductive inks having electrically conductive nano-particles, such as silver nano-particles. The electrically conductive nano-particles can be metallic or have an electrically conductive shell. The electrically conductive nano-particles can be silver, can be a silver alloy, or can include silver.

Curable inks provided in a liquid form are deposited or located in electrical micro-channels **70** and cured, for example by heating or exposure to radiation such as infra-red, visible light, or ultra-violet radiation. The curable ink hardens to form the cured ink that makes up micro-wires **80**. For example, a curable conductive ink with conductive nano-particles is located within electrical micro-channels **70** and heated to agglomerate or sinter the nano-particles, thereby forming an electrically conductive micro-wire **80**. Materials, tools, and methods are known for coating liquid curable inks to form micro-wires **80** in electrical micro-channels **70**. The curable conductive ink is not necessarily electrically conductive before it is cured.

It has been experimentally demonstrated that electrical micro-channels **70** having a width of about 1.8 microns formed in the cured electrical layer **60** with a depth of about four microns are filled with liquid curable conductive inks containing silver nano-particles and cured with heat to form micro-wires **80** that conduct-electricity.

A variety of micro-wire **80** or electrical micro-channel **70** patterns can be used and the present invention is not limited to any one pattern. Micro-wires **80** can be spaced apart, form separate electrical conductors, or intersect to form a mesh electrical conductor on or in a layer. Electrical micro-channels **70** can be identical or have different sizes, aspect ratios, or shapes. Similarly, micro-wires **80** can be identical or have different sizes, aspect ratios, or shapes. Micro-wires **80** can be straight or curved.

In various embodiments, cured inks can include metal particles, for example nano-particles. The metal particles are sintered to form a metallic electrical conductor. The metal nano-particles are silver or a silver alloy or other metals, such as tin, tantalum, titanium, gold, copper, or aluminum, or alloys thereof. Cured inks can include light-absorbing materials such as carbon black, a dye, or a pigment.

Micro-wires **80** can include metal, for example silver, gold, aluminum, nickel, tungsten, titanium, tin, or copper or various metal alloys including, for example silver, gold, aluminum, nickel, tungsten, titanium, tin, or copper. Micro-wires **80** can include a thin metal layer composed of highly conductive metals such as gold, silver, copper, or aluminum. Other conductive metals or materials can be used. Alternatively, micro-wires **80** can include cured or sintered metal particles such as nickel, tungsten, silver, gold, titanium, or tin or alloys such as nickel, tungsten, silver, gold, titanium, or tin. Conductive inks are used to form micro-wires **80** with pattern-wise deposition or pattern-wise formation followed by curing steps. Other materials or methods for forming micro-wires, such as curable ink powders including metallic nano-particles, can be employed and are included in the present invention.

In an embodiment, a curable ink can include conductive nano-particles in a liquid carrier (for example an aqueous solution including surfactants that reduce flocculation of metal particles, humectants, thickeners, adhesives or other active chemicals). The liquid carrier is located in micro-channels and heated or dried to remove liquid carrier or treated with hydrochloric acid, leaving a porous assemblage of conductive particles that are agglomerated or sintered to form a porous electrical conductor in a layer. Thus, in an embodiment, curable inks are processed to change their material compositions, for example conductive particles in a liquid carrier are not electrically conductive but after processing form an assemblage that is electrically conductive.

Once deposited, the conductive inks are cured, for example by heating. The curing process drives out the liquid carrier and sinters the metal particles to form a metallic electrical conductor. Conductive inks are known in the art and are commercially available. In any of these cases, conductive inks or other conducting materials are conductive after they are cured and any needed processing completed. Deposited materials are not necessarily electrically conductive before patterning or before curing. As used herein, a conductive ink is a material that is electrically conductive after any final processing is completed and the conductive ink is not necessarily conductive at any other point in the micro-wire formation process.

In various embodiments of the present invention, micro-channels or micro-wires have a width less than or equal to 10 microns, 5 microns, 4 microns, 3 microns, 2 microns, or 1 micron. In an example and non-limiting embodiment of the present invention, each micro-wire is from 10 to 15 microns wide, from 5 to 10 microns wide, from one micron to five microns wide or from one/half micron to one micron wide. In some embodiments, micro-wires **80** can fill electrical micro-channels **70**; in other embodiments micro-wires **80** do not fill electrical micro-channels **70**. In an embodiment, micro-wires **80** are solid; in another embodiment micro-wires **80** are porous.

Electrically conductive micro-wires **80** of the present invention are electrically connected through electrical contacts **44** to integrated circuits **40** and electrical connectors to electrical circuits that provide electrical current to micro-wires **80** and can control the electrical behavior of micro-wires **80** and integrated circuits **40**.

In embodiments of the present invention, the integrated circuit **40** is formed on an integrated circuit substrate distinct and separate from the substrate **10**, for example a semiconductor substrate such as silicon formed in a semiconductor fabrication facility separately from the substrate **10** that is, for example, glass or plastic. The integrated circuit **40** can include digital or analog electrical circuits electrically connected to one or more of the electrical contacts **44** and to the optical transceiver **42**. For example, the integrated circuit **40** is a digital logic circuit. The integrated circuits **40** of embodiments of the present invention can be placed in a variety of locations and with different orientations. In an embodiment, the integrated circuits **40** are small (e.g. with a dimension less than or equal to 10, 20, 30, or 50 microns).

Integrated circuits **40** can have a crystalline substrate to provide higher performance active components than are found in, for example, thin-film amorphous or polycrystalline silicon devices. Integrated circuits **40** can have a thickness of 100 um or less, preferably 50 um or less, and in some embodiments 20 um or less or 10 um or less. This facilitates formation of the adhesive and planarization material over the integrated circuits **40** that can then be applied using conventional spin-coating techniques. According to one embodiment of the present invention, the integrated circuits **40** formed on crystalline silicon substrates are arranged in a geometric array and adhered to a device substrate (e.g. **10**) with adhesion or planarization materials. Electrical contacts **44** on the surface of the integrated circuits **70** are employed to connect each the integrated circuits **40** to signal wires, power busses, or micro-wires **80**.

In an embodiment, the integrated circuits **40** are formed in a semiconductor substrate and the circuitry of the integrated circuits **40** is formed using modern lithography tools. With such tools, feature sizes of 0.5 microns or less are readily available. For example, modern semiconductor fabrication lines can achieve line widths of 90 nm or 45 nm and can be employed in making the integrated circuits **40** of the present invention. The integrated circuits **40**, however, also requires electrical contacts **44** for making electrical connection to the micro-wires **80** once the integrated circuits **40** are assembled onto the substrate **10** or layers formed on the substrate **10**. The electrical contacts **44** can be sized based on the feature size of the lithography tools used on the substrate **10** (for example 5 um) and the alignment of the integrated circuits **10** to the micro-wires **80** (for example +/−5 um). Therefore, the electrical contacts **44** can be, for example, 15 um wide with 5 um spaces between the electrical contacts **44**. This means that the electrical contacts **44** will generally be significantly larger than the transistor circuitry formed in the integrated circuits **40**.

In an embodiment, the optical transceivers **42** are formed in an integrated circuit **40**. In another embodiment, the optical transceivers **42** are formed on a semiconductor substrate without additional electronic elements. The optical transceivers **42** can be light-emitting diodes, either integrated or individual. The optical transceivers **42** can be edge-emitting or surface-emitting. Methods and devices for forming and providing integrated circuits **40** and light-emitting diodes, both edge- and surface-emitting, are in the photo-lithographic arts and such methods and devices are useful with the present invention.

The imprinted optical micro-channel structure **5** of the present invention is useful in constructing opto-electronic systems formed on the substrate **10** and can be operated to form information processing, display, or input systems. The imprinted optical micro-channel structure **5** of the present invention is also useful in computing and communication systems.

Methods and devices for forming and providing substrates **10** and coating substrates **10** are known in the photo-lithographic arts. Likewise, tools for laying out electrodes, conductive traces, and connectors are known in the electronics industry as are methods for manufacturing such electronic system elements. Hardware controllers for controlling integrated circuits **40** and optical transceivers **42** and software for managing integrated circuits **40** and optical transceivers **42** are known. All of these tools and methods can be usefully employed to design, implement, construct, and operate the present invention. Methods, tools, and devices for operating integrated circuit and opto-electronic systems can be used with the present invention.

The present invention is useful in a wide variety of electronic devices. Such devices can include, for example, computers, communication devices, photovoltaic devices, OLED displays and lighting, LCD displays, plasma displays, inorganic LED displays and lighting, electrophoretic displays, electrowetting displays, dimming mirrors, smart windows, transparent radio antennae, transparent heaters and other touch screen devices such as capacitive touch screen devices.

The invention has been described in detail with particular reference to certain embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

L length direction
5 imprinted optical micro-channel structure
10 substrate
11 substrate surface
20 cured/curable optical layer
21 layer
22 reflective layer
30 optical micro-channel
31, **31**A, **31**B, **31**C light-pipe
32 reflective micro-channel wall

34 curved micro-channel portion
36 angled micro-channel portion
38 optical structure
40, **40**A, **40**B, **40**C integrated circuit
42 optical transceiver
42A optical transmitter
42B optical receiver
44 electrical contact
50 light-absorbing layer
60 cured/curable electrical layer
70 electrical micro-channel
80 micro-wire
82 reflective micro-wire
100 provide substrate step
101 provide integrated circuit step
103 form light-absorbing layer
105 form curable layer step
110 imprint curable layer step
111 imprint integrated circuit structure step
115 cure curable layer step
116 form electrical layer step
117 imprint and cure electrical layer step
118 locate electrically conductive material step
119 cure electrically conductive material step
120 locate curable light-transparent material step
121 locate integrated circuit step
125 form light-pipes step
130 locate optical transmitter and receiver step
131 cure and shrink curable light-transparent material step
135 form reflective layer step
136 form reflective layer step
140 electrically connect electrical contact step
200 form cured optical layer step on substrate
201 form cured optical layer on cured electrical layer step
210 form cured electrical layer step on substrate
211 form cured electrical layer on cured optical layer step

The invention claimed is:

1. An imprinted optical micro-channel structure for transmitting light to an optical receiver or receiving light from an optical transmitter, comprising:

a substrate;

a cured optical layer formed in relation to the substrate, the cured optical layer including one or more optical micro-channels imprinted in the cured optical layer, each optical micro-channel including a cured light-transparent material forming a light-pipe that transmits light in the optical micro-channel;

one or more integrated circuits having one or more optical transceivers, each optical transceiver located in alignment with at least one associated light-pipe, the optical transceiver transmitting light into the associated light-pipe or receiving light from the associated light-pipe; and

a cured electrical layer in contact with the cured optical layer, the cured electrical layer including electrical micro-channels imprinted in the cured electrical layer, the electrical micro-channels including a cured electrically conductive material forming micro-wires in the electrical micro-channels.

2. The imprinted optical micro-channel structure of claim **1**, wherein the integrated circuit includes one or more electrical contacts, each electrical contact electrically connected to at least one micro-wire.

3. The imprinted optical micro-channel structure of claim **1**, wherein the cured electrical layer is located between the cured optical layer and the substrate.

4. The imprinted optical micro-channel structure of claim **1**, wherein the cured optical layer is located between the cured electrical layer and the substrate.

5. The imprinted optical micro-channel structure of claim **1**, wherein at least one micro-wire is reflective and is located to reflect light transmitted by an optical transceiver.

6. The imprinted optical micro-channel structure of claim **5**, wherein the at least one reflective micro-wire is located along the length of an optical micro-channel.

7. The imprinted optical micro-channel structure of claim **5**, wherein the at least one reflective micro-wire is located to reflect light from the optical transceiver to the light-pipe.

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